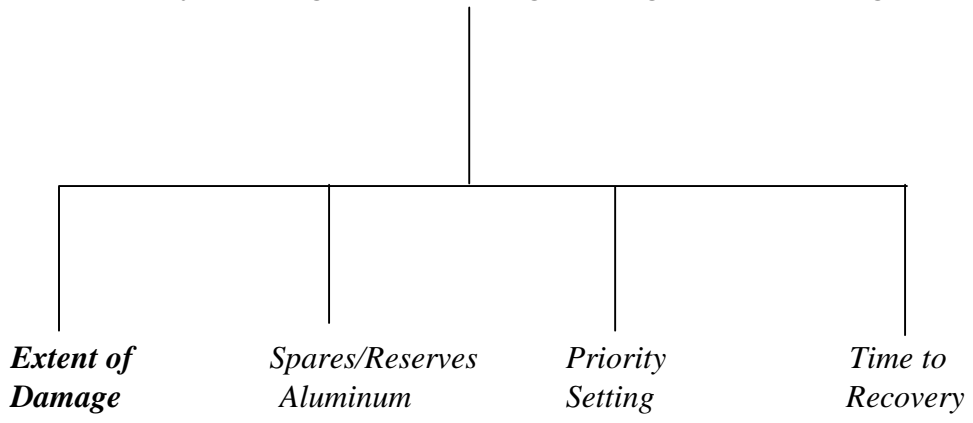


Chapter 2

Alternatives for Reinforcement of Highway Sign Structures

Recovery Management of Signs, Signals, and Lights



2.1 Introduction

The objective considered here is to analyze impacts of different storm categories to highway signs and characterize the extent of damage for these scenarios. This analysis lends itself toward an illustration of trade-offs among possible strengthening alternatives, including the reinforcement of damageable equipment against the threat of hurricane-force wind speeds.

Currently, there is no such documentation or methodology that can predict the extent of damage to signs following a hurricane strike of a given category. Knowing the amount of damage that a given type of hurricane will inflict is an essential aspect of hurricane preparedness. While, VDOT already has a general idea of the extent of damage caused by each category of hurricane, a more detailed description of hurricane damage to sign structures is described in this section. This depiction of sign damage is performed through expansion and further study of the Ultimate Wind Velocity analysis (VDOT, 1997). The information gained from this modeling is then parlayed into a depiction of strengthening alternatives.

Comparison of costs and risks of hurricane damage aids in the evaluation of the various reinforcement plans. Through analysis of possible strengthening scenarios, VDOT will have the opportunity to save money in the long run, for stronger signs might mean less damage and less replacement.

2.2 Background

A great deal of information is available on the force of nature known as the

hurricane. For instance, there is widespread knowledge of hurricane categories, wind speeds, preparedness, evacuation, and tracking charts. There is also data available on the history of hurricanes that have hit eastern Virginia in the past 300 years. The U.S. National Hurricane center also has a large database of hurricane-related information.

Furthermore, there is information on the maximum (ultimate) wind speeds that a given piece of road equipment can withstand. VDOT maintains these types of specifications for much of their equipment. Various other sources also contain damage data for maximum wind speeds, and this information will help toward the determination of the overall extent of damage (Simpson, 1981).

A hurricane is defined as an intense storm with pronounced rotary circulation and constant wind speed of at least 74 miles per hour. Hurricanes are usually named to facilitate tracking and information on their locations. If the sustained wind speed of the storm is between 39 and 74 miles per hour it is classified as a tropical storm.

Table 2.1: Hurricane Wind Speed and Storm Surge by Category Number. The Category number can range from one to five, with five being the most destructive, and one being the least destructive (VDOT, 1996).

Storm Surge (ft)	Maximum Sustained Wind Speed (mph)	Category
4-5	74-95	1
6-8	96-110	2
9-12	111-130	3
13-18	131-155	4
18+	156+	5

Also, different categories of hurricanes have different storm surges associated with them. A storm surge is the increase in height of the surface of the sea caused by the forces of the storm and the slope of the continental shelf, which causes the water to rise as it approaches land.

Though Virginia has experienced many hurricanes in its history, in the past one hundred years, there have been no storm strikes greater than Category 3. Of all the hurricanes to reach landfall since 1886, the vast majority of have entered through the Suffolk district. There have been far more low-categorized hurricanes of 1 or 2 and tropical storms than there have been major storms. A Category 5 hurricane is the least likely and most catastrophic of all storm possibilities.

2.3 Technical Approach – Sign Damage

2.3.1 Outline

This section concentrates on the depiction of Ultimate Wind Velocities and their subsequent effect on sign damage. The organization of this section is as follows:

- A sensitivity analysis of the Ultimate Wind Velocities for signs.
- Determination of the effects of a hurricane on sign equipment.
- Characterization of the ranges of sign damage and the average damage percentages.
- Modeling of hurricane categories in terms of extent of damage to each category of sign equipment.

2.3.2 Ultimate Wind Velocity Analysis

Because each category storm consists of a range of wind speeds, the impacts of the various categories are uncertain. For instance, the damage from 97-mph winds is different from 110-mph winds, though they both fall under the rubric of “Category 2.” In addition, because sign and other equipment specifications are given in terms of maximum wind speeds, they are also indiscrete values. For instance, suppose a sign is designed to withstand up to winds of 100 mph. Some of these signs, in actuality, will not collapse until the wind speed is up to 120 mph, and some will be destroyed at a wind velocity less than the standard.

Table 2.2: Expected Failures of Damageable Equipment (VDOT, 1997).

Damageable Equipment	Ultimate Wind Velocities (mph)
Secondary Sign Structures	86
Ground Mounted Sign Structures	86
Informational Sign Structures	86
Traffic Signals	99
Roadway Lighting Standards	99
High Mast Lighting Structures	111
Cantilever Traffic Sign Structures	117
Overhead Sign Structures	121

From the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Structural Supports for Highway Signs,

Luminaries, and Traffic Signals, an analysis was performed by VDOT to determine the structural strength of the above equipment (VDOT, 1997). These structures are not anticipated to fail at wind velocities less than those noted above. However, random failures may occur due to deterioration, unpredictable behavior in materials, or less than optimum fabrication and/or construction practices. The analysis that produced these results assumes that the structure will fail due to bending. Also, failure may occur at *higher* wind velocities than estimated due to conservative design analyses. Additionally, the analysis does not account for the possibility of foundation failure due to saturated soil conditions resulting from extended periods of precipitation, anchor bolt failure, or other secondary component failures.

For the purposes of this study, the relevant sign standards are given in Table 2.3.

Table 2.3: Expected Failures of Sign Equipment (VDOT, 1997).

Damageable Equipment	Ultimate Wind Velocities (mph)
Roadside Sign Structures	86
Cantilever Sign Structures	117
Overhead Sign Structures	121

The analysis that produced these figures is based on ASSHTO standards and is found in the Hurricane Damage Assessment Manual (VDOT, 1997).

The main ambiguity in the calculations found here is the value of F_u (Unit Ultimate Stress). From the manual, “This analysis does not account for the range between

guaranteed and actual F_u” (See Appendix B).

Equation 2.1 is the formula that VDOT uses to calculate the Ultimate Wind Velocities. As stated above, the variable F_u represents the unit ultimate stress. The variable V represents design Wind Speed per AASHTO MPH. F_{bII} is the unit allowable stress for Group II loading conditions. W_{lr} is the assumed unit load stress divided by F_{bII} . Finally, D_{lr} is the assumed unit dead load stress divided by F_{bII} .

Equation 2.1: Ultimate Wind Velocity (V_u) Formula (VDOT, 1997)

$$V_u = \frac{\sqrt{\frac{(1.3 \times V) \times (F_u - F_{bII} \times D_{lr})}{F_{bII} \times W_{lr}}}}{1.3}$$

Varying the value of F_u by a difference of 20%, it can be seen that the value of V_u (ultimate wind velocity) changes by only about 10%. Consequently, though the value of V_u is not particularly sensitive, the ambiguity of F_u must still be taken into account when characterizing the extent of sign damage for a given category or wind velocity.

2.3.3 Characterization of Sign Damage

From the above findings, although the ultimate wind velocities for signs are given as discrete values, in actuality, the damage needs to be characterized over a range of values.

A discrete representation of the damage percentages is shown in Figure 2.2.

Though this is one simple way to represent the damage for a given size sign, it is most likely not indicative of what really occurs when a hurricane strikes.

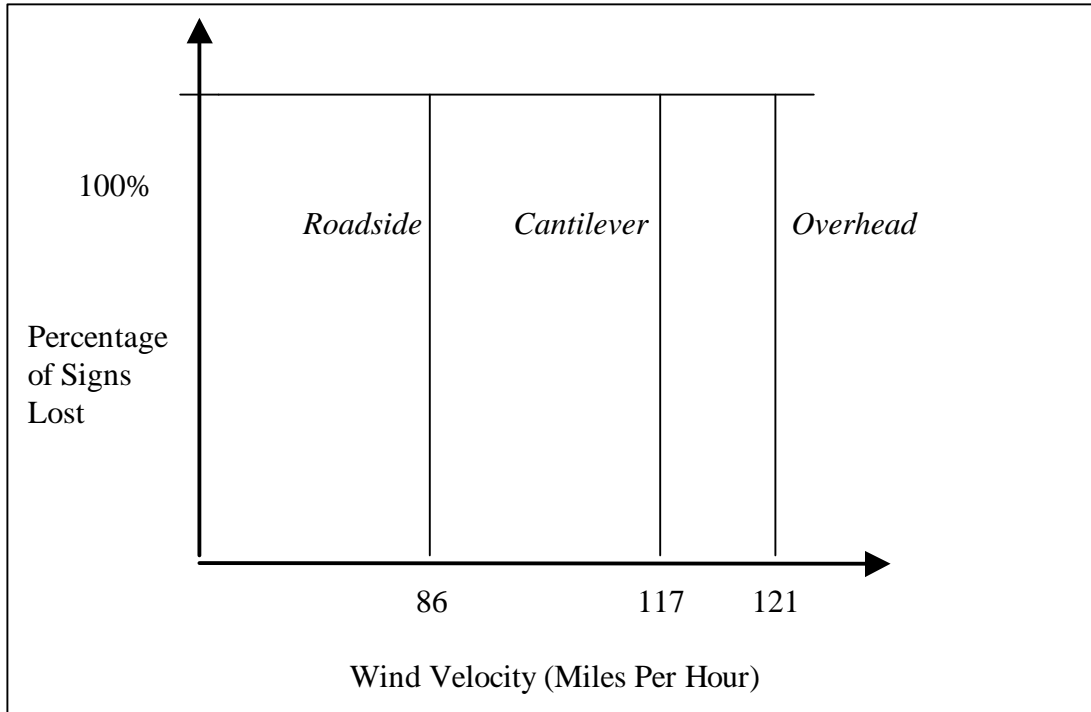


Figure 2.2 A Deterministic Representation of Sign Damage

Though this representation is simple and easy to interpret, a more viable representation of sign damage, however, might be shown through a continuous range of values. In such a depiction, half of the signs might be assumed to be lost at the given ultimate wind velocity. Furthermore, at 90% of the V_u value, one can assume zero damage, and at 110% of the given V_u value, total destruction can be assumed.

This leeway of plus or minus 10% is an assumed range, based upon the uncertainty analysis of F_u in the previous section. This value of 10% may be altered to allow for a greater range of values if a further inspection of the ultimate wind velocities warrant a

change. This 10% value is meant only as a reasonable starting point for further analysis and depiction of subsequent methodology. The three graphs below are a depiction of damage to roadside, cantilever, and overhead signs.

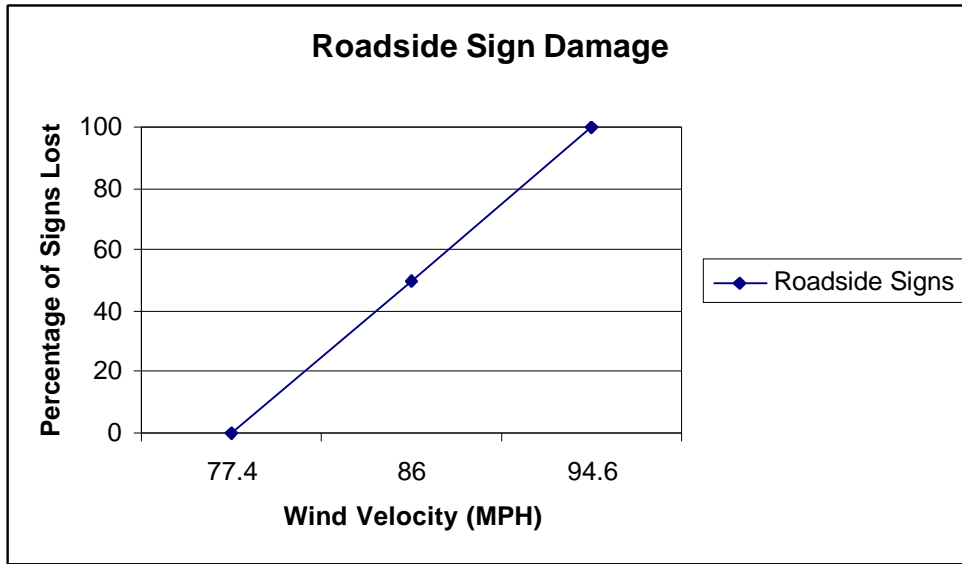


Figure 2.3 A Continuous Representation of Roadside Sign Damage

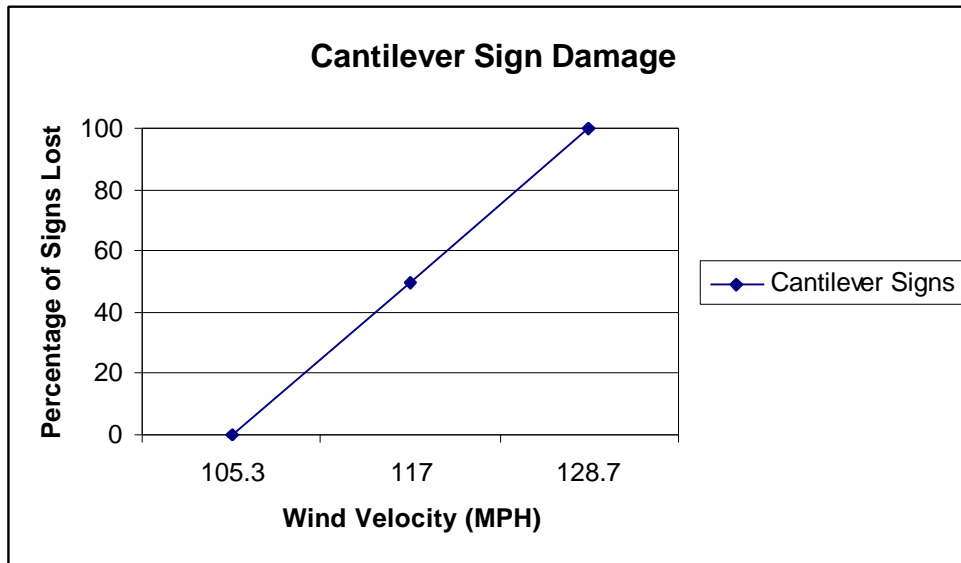


Figure 2.4 A Continuous Representation of Cantilever Sign Damage

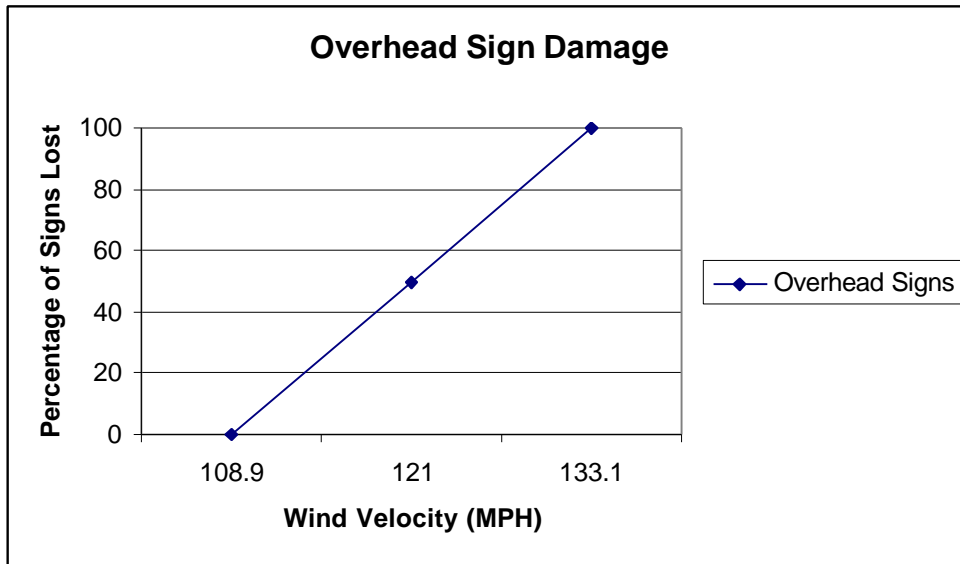


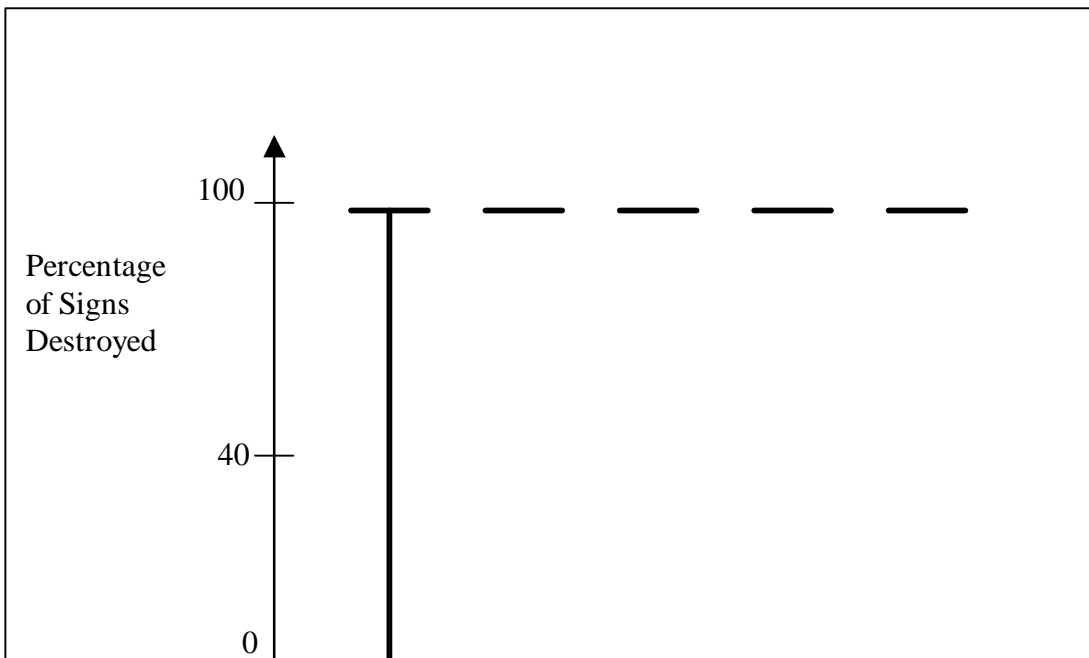
Figure 2.5 A Continuous Representation of Overhead Sign Damage

After characterizing the sign damage in this manner, it is then possible to relate this information to the expected wind speeds for each category of hurricane. This relation can also be depicted as a range of values, with expected damage for minimum, maximum, and average wind speeds in each category. For instance, in a Category 2 hurricane, the wind speeds are between 96 and 110 miles per hour. The average and most likely wind speed (assuming a uniform distribution) would be 103 miles per hour. Using the range of sign damages derived previously, it is possible to now show the expected damage caused by each type of hurricane on each type of sign.

Because the continuous distributions are linear (in this analysis), the damage can be represented through a conditional linear equation represented by $y = mx + b$, with x representing the wind speed, y representing the percentage of signs destroyed, and m and

b represent derived constants, for slope and y intercept. (note: This equation is conditionally linear because it is, intuitively, only linear between the upper and lower bounds of the ultimate wind velocity. At every value below the lower bound, $y = 0$ and at every value above the upper bound, $y = 100$) Once **m** and **b** are derived, any wind velocity (x) can be entered into the equation to output the expected percentage of signs destroyed.

For Roadside sign damage in this example, $y = 5.8x - 550$.



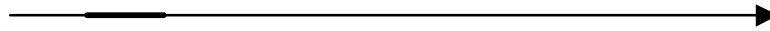
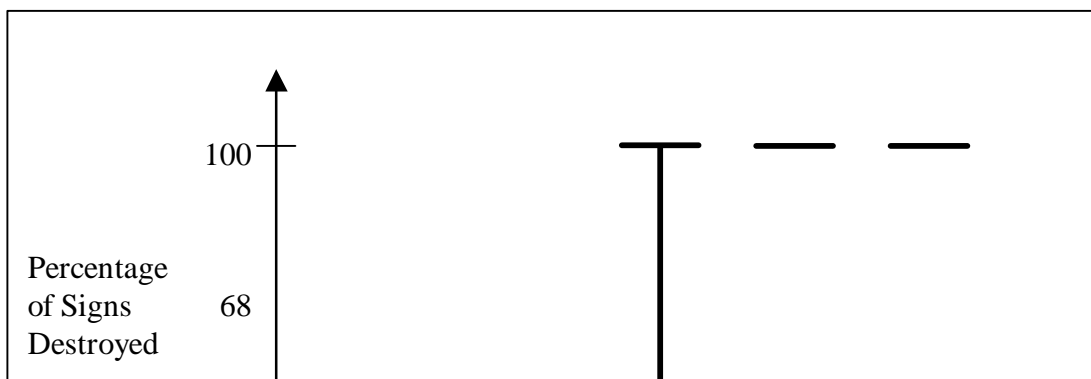


Figure 2.6: Roadside Sign Damage

From Figure 2.6, for Roadside signs, which are the among the majority of the current signs on the highways in Suffolk, the average expected signs destroyed during a Category 1 storm is 40%, with high and low values running the gamut between 0 and 100%. All other categories result in total destruction of roadside signs. Though this result may seem trivial, it is necessary to note that the information in Figure 2.6 will vary along with any change in the aforementioned continuous damage distributions. So depending on the further inspection of the actual variance of the ultimate wind velocity analysis, this result and others can be quite adaptable to the given V_u analysis. The results for Cantilever and Overhead signs under the given assumptions are slightly more interesting.

For Cantilever sign damage in this example, $y = 4.3x - 450$.



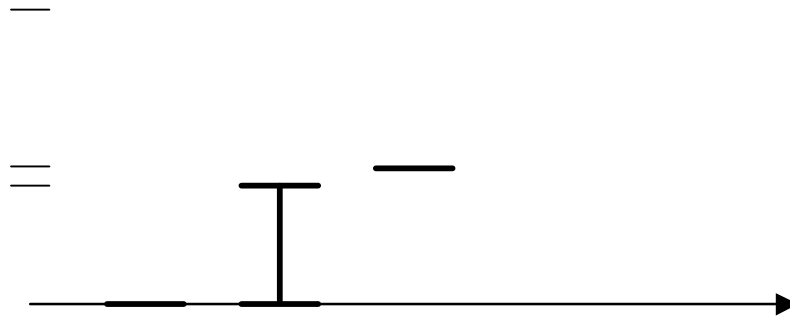


Figure 2.7: Cantilever Sign Damage

(* Note: for category II, the average percent damage is still at 0%, while the upper bound is at 23%)

For Overhead sign damage in this example, $y = 4.1x - 446.5$

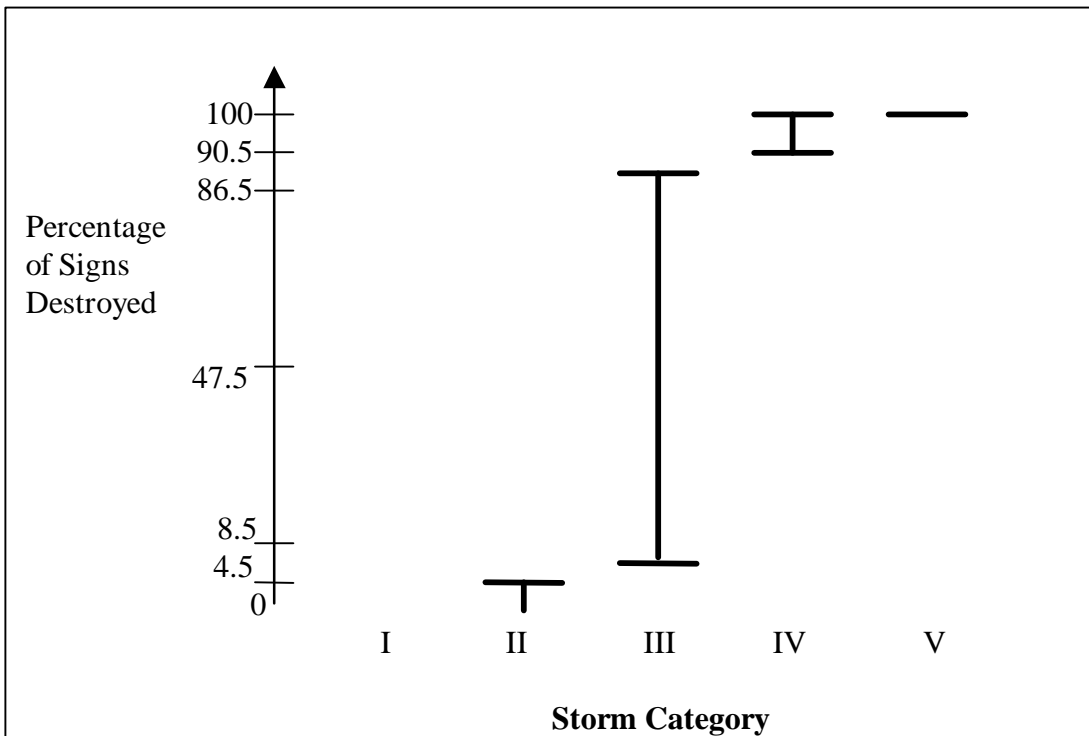




Figure 2.8: Overhead Sign Damage

(*Note: for category II, the average percent damage is still at 0% with upper bound at 4.5%, and for category IV, the average damage is still at 100% with lower bound at 90.5%.)

All of these results are, again, contingent upon the assumption that the Ultimate Wind Velocities (V_u) are fairly accurate, with only a plus or minus 10% error. A change in either the 10% error value or the manner in which the continuous damage distributions are depicted would result in a change in Figures 2.6 – 2.8.

Using this methodology in a manner suitable to VDOT, these results can be subsequently used to help evaluate possible sign reinforcement possibilities.

2.4 Technical Approach – Reinforcement and Strengthening

2.4.1 Outline

This section focuses on one application of an accurate characterization of hurricane damage – namely, the analysis of possible equipment strengthening projects. The organization of this section is as follows:

- Development of a multi-criteria comparison tool with viable criteria and measures of effectiveness.
- Evaluation of possible reinforcement strategies in terms of cost and expected loss of equipment.

2.4.2 Possible Alternatives

When first beginning an analysis of equipment strengthening, one must enumerate the various alternatives available to VDOT. This list of strengthening alternatives is by no means complete; it is only meant as a starting point to start thinking about ways to save money in the long run through reinforcement or strengthening. For each piece of damageable equipment, some options are as follows:

- Retrofit all existing equipment to new much higher standards.
- Retrofit all existing equipment to moderately higher standards.
- Retrofit a given percentage of existing equipment, either moderate or major.
- Design all equipment in the future to new much higher (or moderately higher) standards.
- Replace a percentage of existing equipment that is above a given age limit.
- Do nothing.

Multiple combinations of these scenarios are viable options, as well as all combinations of equipment (all types of signs, signals, and lighting structures).

2.4.3. Evaluation Criteria

In order to perform the analysis, the various data that will be used include:

- Cost of retrofit
- Degree of retrofit
- Lifetime of equipment
- Cost of maintenance

- Wind speeds
- Hurricane frequencies.

One important variable is the monetary cost of strengthening a given piece of equipment. This variable might best be quantified as a percentage of the total current cost of that piece of equipment. For instance, a major retrofit might cost 40% of the initial equipment cost, while a minor one might only cost 20% of the initial cost.

Another important piece of information is the degree to which these structures are hardened. This is represented as a higher maximum wind speed. Also, this variable can be a number representing the increase in resistance. For instance, an index of 20 might be used if a sign was to be retrofitted from an ultimate velocity of 100 mph to 120 mph.

Furthermore, the lifetime of a given structure is also important when deciding if strengthening is cost effective. It will be necessary to estimate how long a given sign might last before and after the retrofit, under non-hurricane conditions.

In addition, the cost of maintaining a given structure also becomes extremely important if the new specifications require a higher degree of maintenance. Also, if current structures were to be replaced, there would have to be a replacement cost associated within such a scenario. Though both of these values can be combined with design costs to form an overall cost variable, it is important that these additional costs not be neglected.

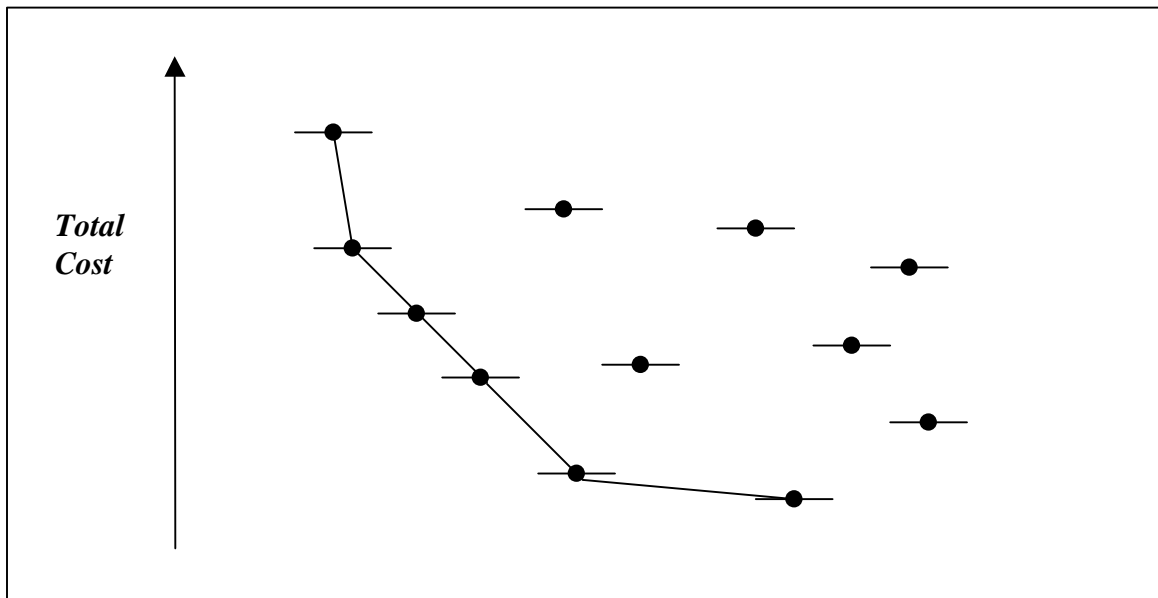
Moreover, in order to construct a viable comparison tool, information would need to be gathered on hurricane frequency and wind speeds. Probability distributions would need to be used to quantify this information accurately. For instance, a distribution of all the recorded wind speeds in a given year can yield a maximum wind velocity for a given non-hurricane strike year. A similar distribution can produce information such as the

maximum wind speed during a hurricane. With these expected values, the expected loss of equipment can be quantified.

Lastly, a rough estimate of the frequency of hurricane strikes to Eastern Virginia is necessary to help determine cost effectiveness. Though a hurricane reaching landfall is rare, and a major hurricane reaching landfall is even rarer, a value must be placed on the frequency of such an event. For instance, a Category 1 hurricane might reach landfall in Suffolk once every 10 years, but a Category 4 hurricane might strike once every 100 years.

2.4.4 Comparison Tool

The objective of this cost-risk analysis is to give VDOT a framework for decision making in the area of reinforcement and strengthening of damageable highway equipment. This framework can be represented by a multi-criteria comparison tool, in which the optimal projects can be identified. Figure 2.9 is an example of such an output from this comparison tool.



—————→
Expected Loss to All Equipment

Figure 2.9: Sample graphical tool used for the comparison of various reinforcement project scenarios.

In Figure 2.9, the vertical axis represents the total cost associated with a given scenario. This cost can include all associated costs, including retrofitting, maintenance, and replacement costs. The horizontal axis represents the risks associated with a scenario in terms of the expected loss to all damageable equipment. Both axes are in terms of a chosen time period under consideration (i.e. “total cost per year”). The symbols (line with point in the middle) are representative of all of the various reinforcement scenarios. The width of these symbols shows the error probabilities of the expected loss to all equipment.

Though there are many aspects of this multi-criteria comparison tool yet to be determined, it can ultimately be used as an effective framework for all of VDOT’s decisions in the area of possible equipment strengthening and hardening.

2.4.5 Representation of Sign Retrofit

A more direct result of the sign damage representation graphs can be developed to compare the costs of various retrofits versus the expected damage from a given storm category. Each type of sign can be strengthened to varying degrees, resulting in positive and negative results - the positive result being less expected damage, and the negative result being a higher cost.

Figure 2.10 shows such a depiction of retrofitting a given sign type to higher standards. In this example, the cost of retrofitting a sign to a 20% higher standard is assumed to equal 20% of the total cost of the sign. Maintenance and other various costs

are ignored in this example, but these additional costs can potentially be incorporated into such a model.

Figure 2.10 shows an example of how overhead signs might be expected to perform, retrofitted to 120% and 140% higher standards. The expected damage from these scenarios can be compared to each other, as well as the 100%, or “do nothing,” option. By comparing the different retrofitting options, one can decide as to whether the decrease in damage is worth the added increase in cost. When this model is actually used in practice, the percent damage would need to be calculated for each retrofit option and the costs would need to be accurately quantified.

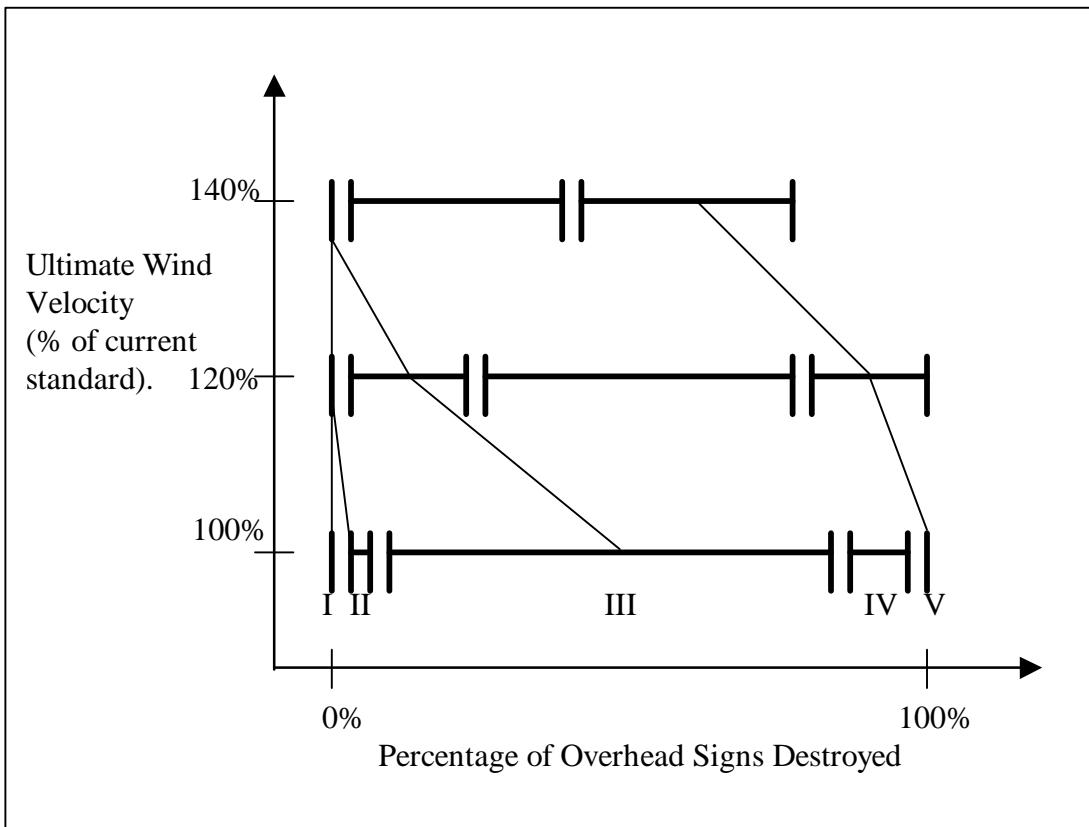


Figure 2.10: Retrofitting Overhead Signs

2.5 Recommendations and Conclusions

The methodologies and models presented here should be considered as a template for further study. These representations and examples of the extent of damage from a hurricane are meant as starting points for those with more experience and data. It is hoped that this document was able to highlight the important issues pertaining to the damage of highway equipment due to hurricane forces.

From the methods shown here, it can be seen that the characterization of hurricane damage is a valuable component of hurricane preparedness and recovery, and it is something that has been overlooked previously. The aspects of these methods that are most in need of further analysis are: the representation of Ultimate Wind Velocity for damageable equipment, the characterization of total equipment damage, and the criteria involved in possible strengthening alternatives.

The characterization of Ultimate Wind Velocity (V_u) is extremely important and is essentially the basis of all subsequent analysis. Because one can not expect every single roadside sign to be destroyed at exactly 86 Miles Per Hour, a continuous/probabilistic distribution must be derived based upon the formula for V_u and basic civil engineering practices. A wholly viable option for such a depiction was presented in this thesis document, but further analysis is recommended. Total equipment damage was also represented as a function and distribution of hurricane storm categories, but, again, this representation is dependent upon the depiction of V_u .

Furthermore, it is recommended that the strengthening and retrofitting alternatives be studied in further detail. The possibility of saving taxpayer money through strengthening and/or retrofitting practices is an extremely attractive scenario to VDOT (Mondul, 1996). Once the necessary criteria are determined, the comparison tools illustrated in this document should serve VDOT with a method of deciding whether such reinforcement alternatives are cost-effective. However, there is still much information that needs to be gathered on this subject, and it is recommended that it, indeed, be studied in greater detail.